A SAMPLE AND HOLD TECHNIQUE FOR AUTOMATIC FREQUENCY CONTROL IN BINARY DATA TRANSMISSION SYSTEMS

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THESIS

A Sample and Hold Technique for Automatic Frequency Control in Binary Data Transmission Systems

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ABSTRACT

A method of deriving a voltage for automatic frequency control of a radioteletype receiver-converter is developed and tested. By sampling and holding the amplitude of the "Mark" and "Space" signals out of an FSK detector, comparing and integrating their difference, an error correcting voltage results which is less sensitive to noise and selective fading than the AFC voltage derived in the usual way. A sample-and-hold circuit is described. Comparative performance tests, with data in the form of strip-chart recordings, confirms the claims made for the technique.

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I. INTRODUCTION

The most widely used method of teletype data transmission is that of frequency shift keying (FSK). This is the best method for use over long transmission paths on a high frequency data link in the presence of noise and selective fading. FSK also has a marked advantage over simple ON-OFF keying for transmission reliability when flat fading is present (Ref. 5). The corresponding binary signal is represented by a shift between two different frequencies or levels that are called "Mark" and "Space", usually for the higher and lower values respectively.

A detector to be used for the demodulation of frequency shifted or frequency modulated signals, that is, a discriminator, is characterized by an "S" curve which shows graphically the relation of output voltage to frequency at the input. The center frequency, when the output voltage is zero, may be the intermediate frequency of the receiver or it may be an audio frequency.

Some converters, used for the keying of teletype printers for example, use 2550 Hz as the center frequency when working with a frequency shift of 850 Hz, or 1000 Hz as the center frequency when using 175 Hz as the frequency shift. Such as "S" curve is shown in Fig. 1.

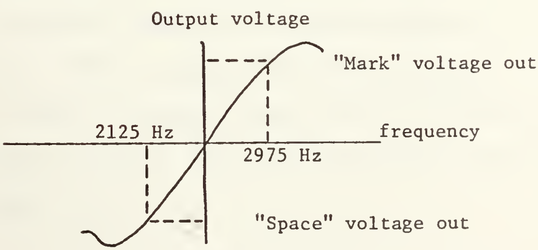


Figure 1. "S" Curve Correctly Centered

The above figure shows that a signal of "Mark" frequency yields a positive output voltage while one of the "Space" frequency yields a negative. Ideally these positive and negative voltages are of the same absolute value. When for any reason, the center frequency drifts, the corresponding Mark and Space voltages become unequal in absolute value. In severe cases either the Mark or the Space may become zero or may actually become of reversed polarity.

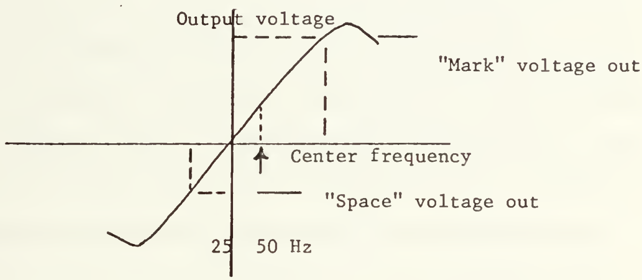


Figure 2. "S" Curve With Center Frequency displaced

This situation can be corrected by retuning the receiver, or by retuning one of the mixing oscillators in the proper direction to bring the center frequency of the signal, fed to the detector, back to the value for which the circuit is designed.

Well engineered receivers or teletype converters incorporate a circuit which integrates the output signal to produce a d-c voltage. This voltage is a measure of the drift and, when fed back to a voltage-controlled-oscillator (VCO), it corrects the center frequency.

If a teletype signal is correctly tuned so as to be centered on the "S" curve, the output voltage as viewed by a Cathode-ray oscilloscope will appear as shown in Fig. 3.

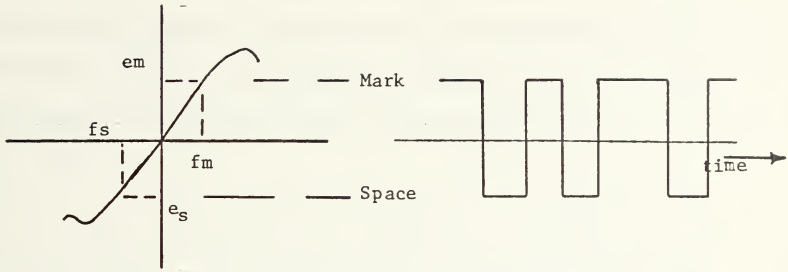


Figure 3. Ideal Teletype Signal Waveform

The actual form of the output will of course depend upon the coded information, the maximum positive value corresponding to Mark and the maximum negative to Space. A character transmitted by teletype occupies a time frame as shown in Fig. 4. Each character is preceded by a start interval which is transmitted as a Space frequency. This is followed by five equal intervals which may be either Mark or Space depending upon the Baudot code for the character transmitted. The time frame ends with a stop period which is transmitted as a Mark frequency.

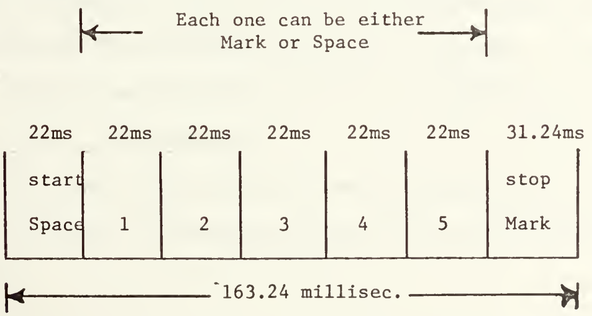


Figure 4. Standard Teletype Code Sequence (60 WPM)

It is possible that the average voltage out of the detector or discriminator will have a value different from zero, even though the signal is correctly centered with respect to the "S" curve. A frequency

correcting voltage, derived in the usual way by integration, will then change the center frequency even though no change is needed or desired.

The frequency correcting voltage is the time integral of $e_m - e_s$. (Fig. 3).

$$e_o = \int (e_m - e_s)\, dt = \int e_m\, dt - \int e_s\, dt$$

This voltage, e_o, is a measure of the long-time difference between the Mark and Space frequencies. The relatively small value of e_o is the result of the difference of $(e_m - e_s)$ in the long-time average.

If, over this period of time, the number of Mark pulses exceeds the number of Space pulses, the integral of the output signal will have a positive value, while if the reverse is true, the integral will have a negative value.

This thesis is a report on an alternate method of obtaining a frequency correcting voltage. It is believed that the method is superior to the conventional one because, while maintaining the desired equality in absolute magnitude of the Mark and Space output voltages, no shift of the center frequency results simply because of a preponderance of Marks over Spaces in the coded message.

It is also believed that the method may have application in the measurement and control of frequency modulated signals and single side-band signals.

II. PROBLEM ANALYSIS

Radioteletype transmission is accomplished by means of frequency-shift-keying the transmitted carrier. This process of FSK consists of changing the transmitted carrier frequency from one frequency, representing the "Mark" condition of the teletype, to another frequency which represents the "Space" condition.

This is a process similar to frequency modulation, and has the advantage of FM as far as noise reduction is concerned. And, although this type of transmission requires more band-width than other methods of modulation, it has the advantages of being very useful for long-distance transmissions in the presence of fading and poor signal-to-noise ratios.

The two frequencies representing Mark and Space conditions can be expressed as:

$$f_c(t) = A\ \mathrm{Cos}_m\ t$$

$$f_c(t) = A\ \mathrm{Cos}_s\ t \qquad -\frac{T}{2} \leq t \leq \frac{T}{2}$$

where $f_c(t)$ = carrier frequency

f_m = Mark frequency

f_s = Space frequency

It is possible to represent these signals as:

$$f_m = f_c + \Delta f$$

$$f_s = f_c - \Delta f$$

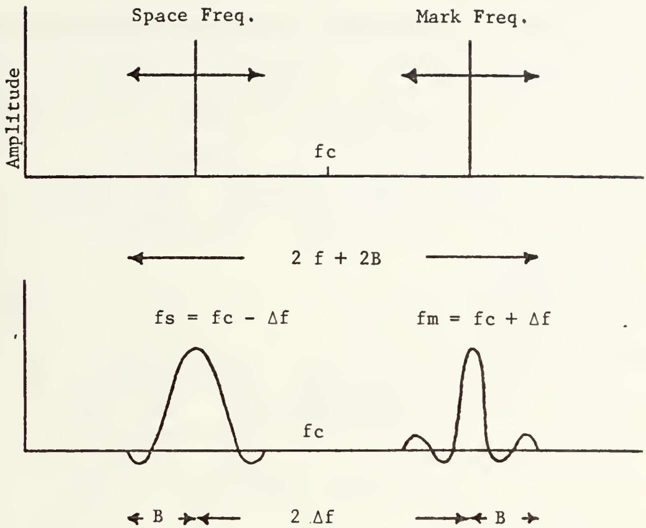


Fig. 5. Two Tone FSK

Then, the mark and space signals differ by $2\Delta f$

$$\begin{array}{l} f_m = f_c + \Delta f \\ -\ f_s = -f_c + \Delta f \\ \hline f_m - f_s = 2\Delta f \end{array}$$

Therefore $f_c(t) = A \operatorname{Cos} (\omega_c \pm \Delta\omega)t$

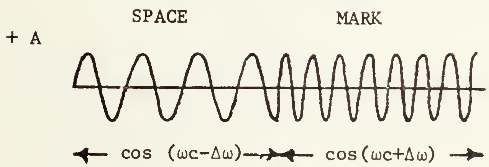


Fig. 6. FSK Representation

Now the problem is how the noise and fading will affect FSK transmissions with envelope detection at the receiver as used in teletype systems. When a Mark is transmitted, the signal-plus-noise are received at channel #1, but at channel #2, only noise.

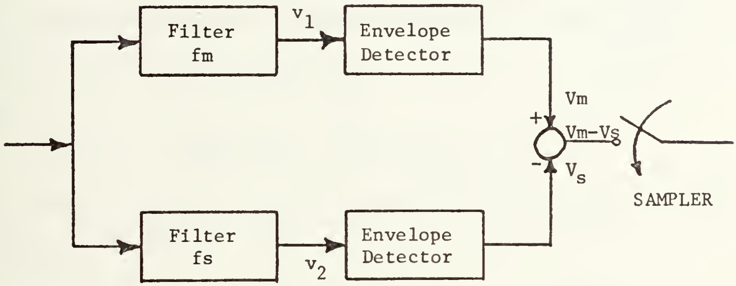


Fig. 7. Non-Coherent FSK Detection

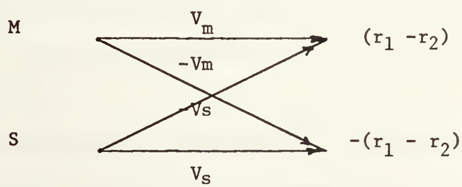
f_m = Mark frequency

f_s = Space frequency

$V_m = s(t) + n_1(t)$ Channel #1

$V = n_2(t)$ Channel #2

For a correct decision by the receiver the value of $V_m - V_s$ should be positive. The reverse situation exists when a Space signal is transmitted. In a teletype transmission, the Mark and Space signals are equally likely to occur. This can be expressed as:



An error will be obtained when a Mark is transmitted and $-(r_1-r_2)$ is received, or when a Space is transmitted and $+(r_1 - r_2)$ is received. Therefore the probability of error is:

$$Pe = \int_{r_1=o}^{\infty} f_s(r_1)[\int_{r_2=r_1}^{\infty} f_n(r_2)\, dr_2] \qquad \text{(Ref. 3)}$$

and since $f_n(r)$ is a Rayleigh probability density, we have:

$$\int_{r_2=r_1}^{\infty} f_n(r_2)\, dr_2 = e^{-r_1^2/2N}$$

Then:

$$Pe = \int^{\infty} \frac{r_1}{N} e^{-r_1^2/N} e^{-A^2/2N} I_o\left(\frac{r_1 A}{N}\right) dr,$$

and setting $x = \sqrt{2}\, r_1$, and comparing with the Rician density function, we obtain:

$$Pe = 1/2 \;\; e^{-A^2/4N} \qquad \text{(II-1)}$$

This shows that the probability of error due to noise has an exponential variation dependent on the noise power imposed on the signal, and the larger the exponential factor, the lower the probability of error will be.

As can be observed from Fig. 7 , in binary FSK systems, such as teletype, the two frequencies transmitted are detected separately by means of a discriminator or other type of detector applicable to the case.

However, noise is not the only interference data transmission has in FSK systems. These systems are used for data transmission at high radio frequencies through channels possessing fading characteristics and are subject to multipath interference due to reception by other than the dominant signal path.

Because one objective of this study is to avoid in some degree the effects of selective fading in an HF communication link, let us consider briefly how fading affects radioteletype, and in general any binary transmission.

Assuming for simplicity that the channel has Rayleigh fading, which causes the amplitude of the received signal to vary according to the Rayleigh distribution, but for simplicity also, let us consider the amplitude of the transmitted signal to be constant. Then if to the signal in a fading channel, is added a gaussian noise, the average probability of error is given by:

$$E\ (P_e) = P_e(A) \frac{Ae^{-A^2/s\ \sigma^2}}{\sigma 2} \ dA.$$

$$= 1/2\ e - A^2/4N\ \frac{A\ e - A^2/2\sigma^2}{\sigma 2} \ dA$$

$$= \frac{1}{2 + (\sigma^2/N)} \qquad \text{(II-2)}$$

where σ^2 = Mean signal power in the fading path

N = Mean noise power added to the signal

If Eqn. II - 1 is compared with Eqn. II -2, one observes that the latter varies inversely as the signal-to-noise ratio, while the former varies exponentially. Then the probability of error has been greatly increased in the presence of fading.

Both noise and the phenomena of selective fading affects a teletype data transmission, increasing the probability of error which is expressed as a misprinting due to a loss of a portion of the code. When such a loss occurs, a signal will be generated at the output of the discriminator circuit of the teletype converter, which is an error correcting voltage to be used for AFC (Automatic Frequency Control), just the same as would result from a drift in the value of the center frequency of the signal.

Now the question arises, do we really need an error correcting voltage for AFC when an apparent frequency drift is generated due to fading or interference? The answer is of course that such a voltage is not necessary because it will retune the BFO or the HF oscillator to an incorrect frequency, which is undesirable.

A. DESCRIPTION OF CONVENTIONAL AFC

In order to make a comparison, let us see how a standard AFC error correcting voltage is generated. There exist, actually, several ways of obtaining an error correcting voltage. However, since most are quite similar, for recognition purposes they will be called in this report, the "Conventional" method. To describe in very brief form how these conventional circuits perform, we have selected that used in the CV-115/URR Radioteletype Converter. The simplified circuit diagram is shown in Fig. 8.

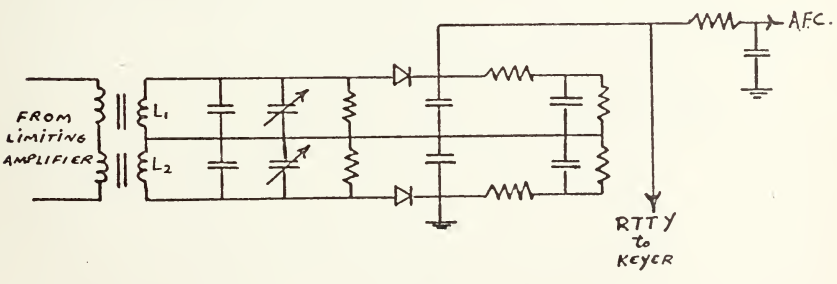


Figure 8. Deriviation of AFC Error Correcting Voltage

The secondaries L_1 and L_2 are tuned by capacitances to the Mark and Space frequencies. Diodes D_1 and D_2 detect these signals when present and, because of the ground connection, give a positive voltage to the keyer when a Mark is received and a negative voltage when a Space frequency is received.

From the same point the AFC voltage is obtained. However, this voltage is filtered by a long time-constant circuit so that the actual AFC error correcting voltage can vary only slowly and is therefore the long-time average of the positive Mark signals and the negative Space signals fed to the keyer. If a steady Mark frequency is received, the AFC voltage will assume a constant positive value while if a steady Space frequency is received, it will become a constant negative value.

III. SAMPLE AND HOLD TECHNIQUE

As was observed previously, the error correcting voltage e_o, obtained for automatic frequency control, generally is a measure of the long-time difference between the Mark and Space frequencies. This value, e_o, varies slowly about some central value during the reception of binary Mark-Space signals. An alternative method of obtaining a frequency correcting voltage will be described here.

The holding circuit, as will be seen in detail, will yield the peak value of the Mark and the Space signals, rather than the time-average values. This is possible because samples of these peak values are taken simultaneously and maintained through the circuit for any desired time. The holding period can be easily controlled by changing some component values. Basically, the work performed is indicated in Fig. 9

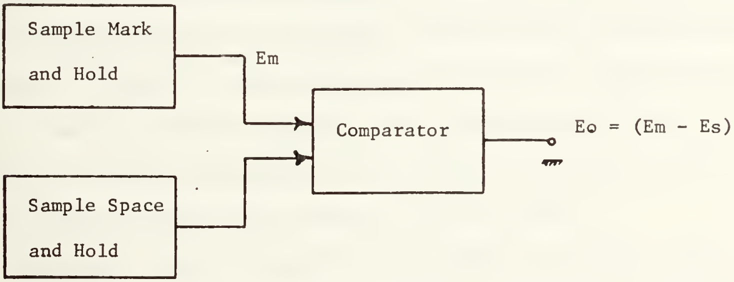


Fig. 9. Function of the Sample and Hold Technique

If the two peak values are combined in order to get their sum, one obtains an error correcting voltage E_o which will depend upon the amplitudes of the Mark and Space signals, which of course depend upon the input frequencies. Then, if the input frequencies have the correct

values, as is shown by the "S" curve, the peak values of the Mark and Space signals will be equal and opposite in sign, giving at the comparator a zero error correcting voltage.

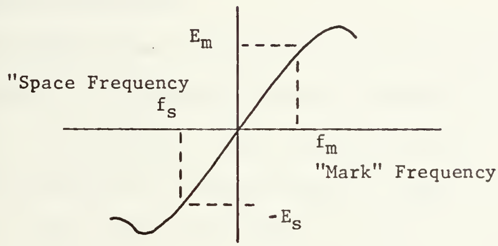


Figure 10. "S" Curve Representation

However, if any drift occurs, the corresponding values of E_m and E_s will be different as indicated for e_m and e_s in Fig. 2. The value of E_o represents, just as e_o does, a measure of the long-time average difference between the Mark and Space frequencies. But now, because the peak values of the signals are being held during a certain period, the value of E_o will not be affected by the preponderance of Marks or Spaces during the same interval, eliminating in this sense, the production of an error correcting voltage when such is not required. That is, when the signals are correctly centered with respect to the "S" curve.

This error, which corresponds to the amount of frequency drift, is a d-c value that can be used to drive the BFO or HF oscillator in the proper direction necessary to make the correction and center the signals with respect to the "S" curve. As another advantage of this method, it may be noticed that if due to selective fading, the Mark, or Space, signal is lost for a short time, the voltage e_o obtained in the standard

way would sense this immediately, while the effect on E_o, from the sample and hold circuit, would not be apparent unless the fade endured for longer than the holding time.

A. CIRCUIT DESCRIPTION

The diagram shown in Fig. 11 illustrates the basic circuit used for the realization of the sample and hold technique for automatic frequency control. For simplicity, only the positive (Mark) circuit is shown. It consists basically of a combined Schmitt trigger and a one-shot multivibrator formed by the first three transistors, followed by an automatic switch formed by the last transistor and its connections, which acts at the end of the holding period as will be explained.

This circuit, initially has Q_1 OFF and the other transistors ON due to the high collector voltage of Q_1. When the positive peak of the input pulse is applied to the circuit, the capacitor C_2 is charged through the diode D_2. This represents the sampling action. The positive peak also performs the functions of: Turn Q_1 ON, Turn Q_2 OFF, making the capacitor C_1 begin charging through the 3 K ohm collector resistor directly from the + 6 volt supply. The charging current of C_1, through the 22 Kohm base resistor of Q_3, is of such a direction as to turn OFF this transistor. Due to this action, the collector voltage of Q_3 is low and the base voltage of Q_4 is made low by d-c coupling. This also makes D_1 conduct and holds Q_2 OFF, cauisng also Q_4 to pass to the OFF condition. In this manner the holding action is obtained, since C_2 is not permitted to discharge.

As capacitor C_1 charges, the base voltage of Q_3 changes with a time constant equal to:

$$\zeta = C_1(3K + 22K)$$

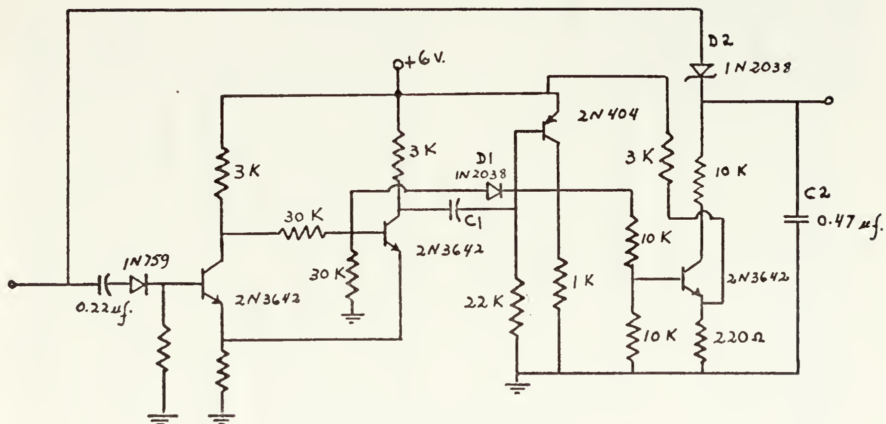


Figure 11. Positive Holding Circuit

After some time, Q_3 turns ON. This causes Q_4 to conduct and therefore to discharge C_2. Also D_1 no longer conducts and Q_2 goes ON. In this situation the circuit is then ready for another sample.

B. PERFORMANCE TEST

A system to test the performance of the holding circuit is shown in the block diagram of Fig. 12 which includes a function generator that will give a bipolar, square wave, a signal representing the teletype signal. This waveform is shown in Fig. 13.

The signal can be changed in amplitude and in this case, a value of 8 volts, peak-to-peak was chosen as a reference. The frequency can also be changed but because the duration of a Mark or a Space in teletype transmission is about 22 milliseconds, with a total period of 44 milliseconds, a frequency of 23 Hertz was chosen. The signal therefore, simulates a teletype transmission and is fed simultaneously to both the positive and negative holding circuits.

The outputs of these circuits, which can be observed with a dual-beam oscilloscope, are shown in Fig. 14. Notice that after the holding period, which is adjustable by changing C_1, there is a period that corresponds to the discharge of C_2. This corresponds approximately to the interval marked as STOP in the standard teletype code sequence shown in Fig. 4.

It can be observed also that there exists a time difference between the two output signals. This is because the negative peak of the bipolar signal out of the function generator is fed to the negative holding circuit with a delay corresponding to the time constant of that circuit. The holding period of this test was set at about 100 milliseconds merely for convenience. As noted it can be made as long as desired.

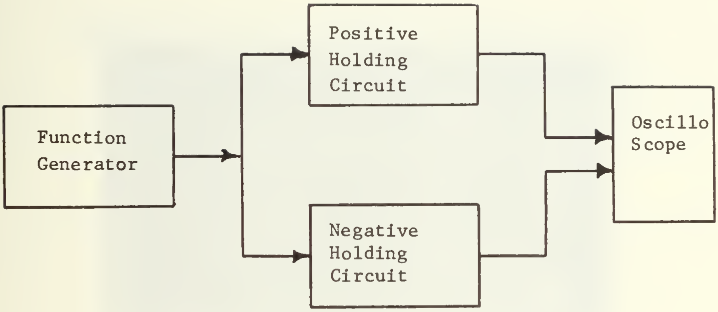


FIG. 12. Block Diagram of Test Circuit

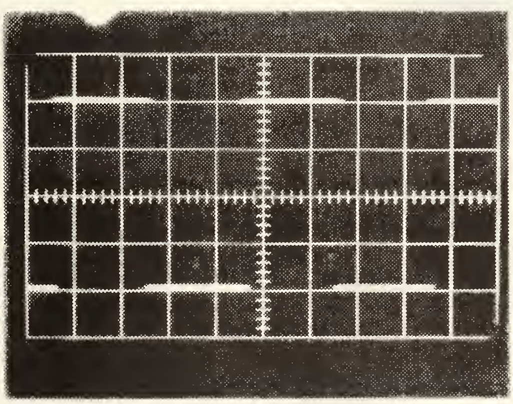


FIG. 13. Bipolar Signal Waveform

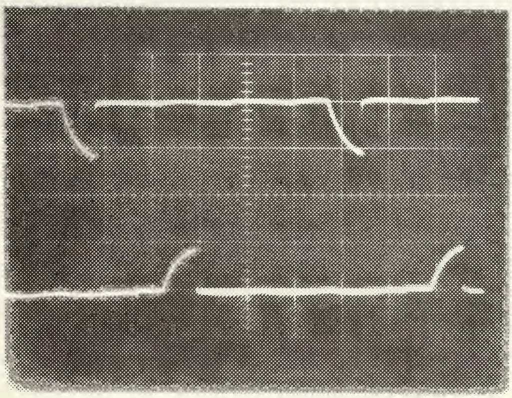


Figure 14. Output of Positive and Negative Holding Circuits

IV. EXPERIMENTAL RESULTS

The physical realization of the basic concept of automatic frequency control by the use of the sample and hold technique confirms that this alternate method is simple and practical. The circuit responses, shown in the previous chapter, indicate that the construction of the holding circuit for obtaining E_o is feasible and easy to accomplish.

The results reported here are laboratory tests. To obtain the teletype signal, a communications receiver, R-1051B/URR, was used. It was conditioned with a remote fine tuning unit in order to be able to obtain frequency changes within an accuracy of o.2 Hz, as explained in detail in Ref. 6. The frequency display is complemented by the use of a digital frequency counter for measurement of vernier frequencies.

The signals used in testing and comparing were pre-recorded for convenience and because of the difficulty in obtaining a continuous reception from a distant station at the time we desired to make a test. Therefore, the recorded signals were those available at that time but the same results can be obtained by tuning the receiver to any other station. Actually the test was performed with the recorded signals from two different stations.

The recorded signal is passed to a converter (AN/URA-17), from which is obtained the voltage necessary to operate the teletype keyer. In order to make a comparison between the standard AFC system and the sample-and-hold method described here, the teletype signal received was taken from test point TP-4, (Fig. 6-5, Ref. 8) this point was selected because of the 0.0 d-c reference level around which the signal goes up and down. As is

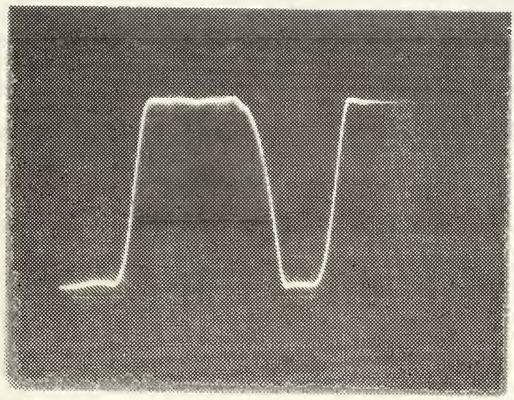


Figure 15. Received Teletype Signal

indicated in Fig. 15 the signal at TP-4 is not a perfectly symmetrical square waveform as was the signal obtained from the function generator as can be observed in Fig. 13.

The signal obtained out of test point TP-4 (Fig.7) reaches an amplitude of about 40 volts peak. This is controlled by the use of a potentiometer to any desired level to suit the circuits and components being used. This signal was adjusted to obtain a value close to that of the test signal used in Section II, that is 8 volts peak-to peak.

As indicated in the block diagram of Fig. 16, which shows the complete set-up used for the comparison, after the signal out of the converter has been adjusted by the amplitude regulator, it is injected at the same time to both channels of comparison, that is, the standard AFC and the sample-and-hold circuit.

In order to get the same sensitivity for proper comparison, a sensitivity regulator has been provided at the input to the standard AFC circuit. The output of this standard circuit corresponds to e_o in the way described in the Introduction. That is, by a long time integration of the difference between the Mark and Space frequencies. The way in which this value changed according to the signal itself, and due to any drift resulting from some interference such as noise or selective fading during the reception, was recorded with a Clevite - 220 dual pen recorder.

The amplitude-regulated received signal is injected at the same time to both holding circuits, in which the respective values of Mark and Space are held for some time, obtaining during this time an output corresponding to E_m or E_s, which are insensitive to any change during the holding period.

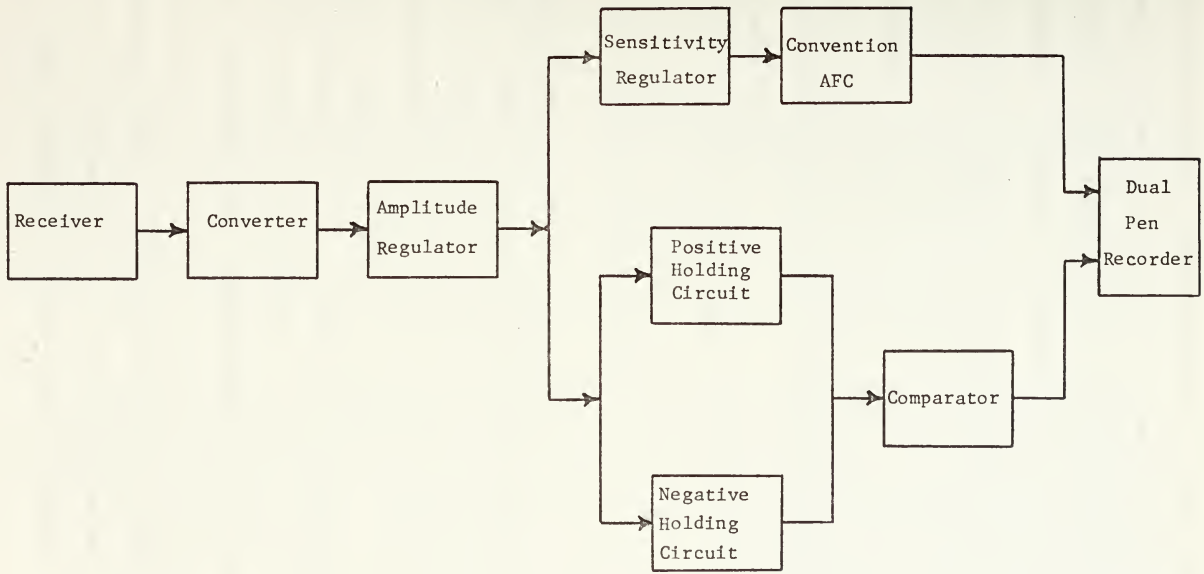


Fig. 16. Block Diagram of Comparison Test Circuit

The signals obtained from the respective holding circuits are combined in a comparator that in this case acts as an adder, giving E_o as its output. This value was obtained using the same time constant in the comparator as that used in obtaining e_o from the standard AFC circuit in order to make a fair comparison. This error correcting voltage, E_o is also injected at the same time that e_o is, into the pen recorder which actually records the way in which the two systems respond to the changes in frequency of the teletype signal being received.

For testing the circuits under different conditions, three different curves were obtained.

(a) Receiver properly tuned

(b) Receiver mistuned

(c) Frequency changes randomly

A. RESPONSE WHEN RECEIVER IS PROPERLY TUNED

Fig. 17 shows the error correcting voltage generated by both circuits when the receiver is properly tuned to the transmitting station. Tuning was actually tested by sending the pre-recorded signal to a teletype printer and observing the quality of the print.

From the figure it will be observed that the sample-and-hold error correcting voltage is more insensitive to the variations due to the change in amplitude of the teletype signal resulting from its non-symmetrical square-wave form. One also observes a large change in the corresponding value of e_o which can be caused by a momentary frequency drift due to selective fading or other interference such as noise. This abrupt change, according to the scale used in recording of the signals,

SCALES: SENSITIVITY = 100 mv/div

SPEED = 25 mm/sec

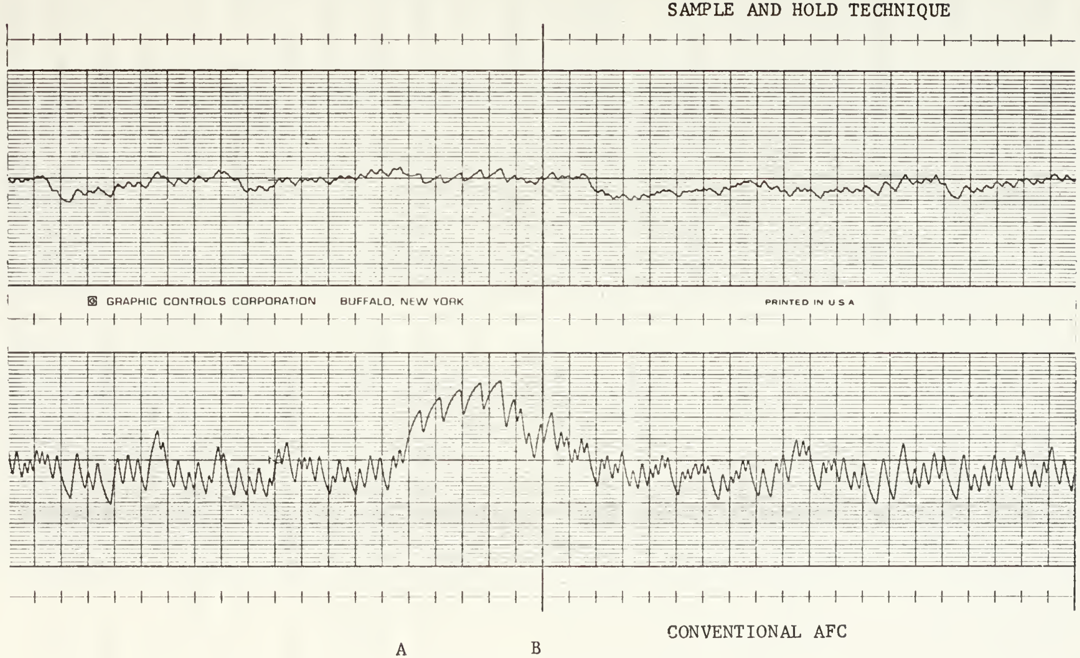


FIG. 17 RESPONSE WHEN PROPERLY TUNED

has a duration of 1 second. For purposes of comparison the holding period used in both the positive and the negative holding circuits was 2.5 seconds. This is a very long time but it permits us to see, as pointed out before, that if the fade or interference is less than the holding period, it will have no effect on the value of E_o.

B. RESPONSE WHEN RECEIVER IS MISTUNED

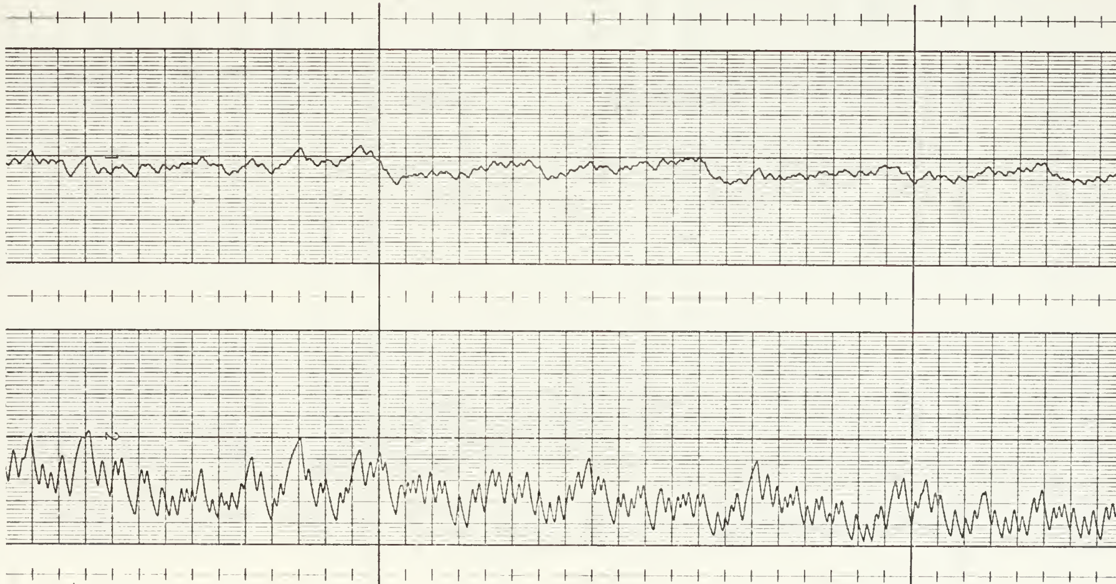
Fig. 18 shows the error correcting voltage when the receiver is mistuned to a frequency at which the print-out contains an excessive number of errors. These errors, as previously indicated, are caused by the level displacement of the signal above or below its 0.0 d-c volt reference. The integration of the corresponding amplitudes of Mark and Space signals by the conventional method, will generate an error correcting voltage which will retune the BFO or HF oscillator to a frequency for proper centering of the signal on the "S" curve.

As can be observed in the corresponding comparison graph, the error signal generated by the conventional method is one that follows every change in amplitude due to the non-symmetry of the teletype signal, at a level displaced from that corresponding to the center value. This error correcting value, which is not a real one because it does not correspond to any drift in frequency in the receiver due to itself (or interferences such as noise or fading), is sensed by the sample-and-hold channel as the recording indicates, but keeping the variation level within a very reasonable value in which the frequency of the oscillator will not be changed abruptly but smoothly. Also, this variation is very near the center value to which the receiver is actually tuned.

SCALES: SENSITIVITY = 100 mv/div

SPEED = 25 mm/sec

SAMPLE AND HOLD TECHNIQUE



CONVENTIONAL AFC

FIG. 18 RESPONSE WHEN MISTUNED

C. RESPONSE WITH RANDOM FREQUENCY CHANGES

If the tuning frequency of the receiver is changed randomly, then a random error correcting voltage is generated and also misprinting occurs due to these changes.

The frequency changes cause the teletype signal, as indicated in Fig.15, to move up or down corresponding to an increase or decrease in frequency respectively. This displacement of the signal, makes the conventional AFC circuit generate an error correcting signal, as shown in Fig. 19, which closely follows the variations of the frequency tuning.

In the chart corresponding to this figure can be observed three different situations corresponding to; a decrease/increase of the frequency, a period at which the receiver is maintained properly tuned, and then an abrupt change and an increase in frequency. The first situation corresponds to the period indicated between points A and B in which the receiver is detuned, decreasing the frequency and then increasing it again to the proper tuning value. While the conventional AFC method follows these frequency changes, with a large amplitude variation and displacements from the 0.0 d-c reference value, the sample-and-hold circuit, although it senses the variation smoothly give a small value in comparison with the other.

Within points B and C, when the receiver is properly tuned, both error correcting voltages vary around the corresponding center value. After point C, when the frequency is increased, the abrupt change of e_o is not observed initially in E_o, which is the voltage from the sample-and-hold path. This is because the change occurred during the holding period. The change is sensed later. It is smooth and the variation from the 0.0 d-c reference level is small because of the short duration of the frequency change.

SCALES: SENSITIVITY = 100 mv/div
speed = 25 mm/sec

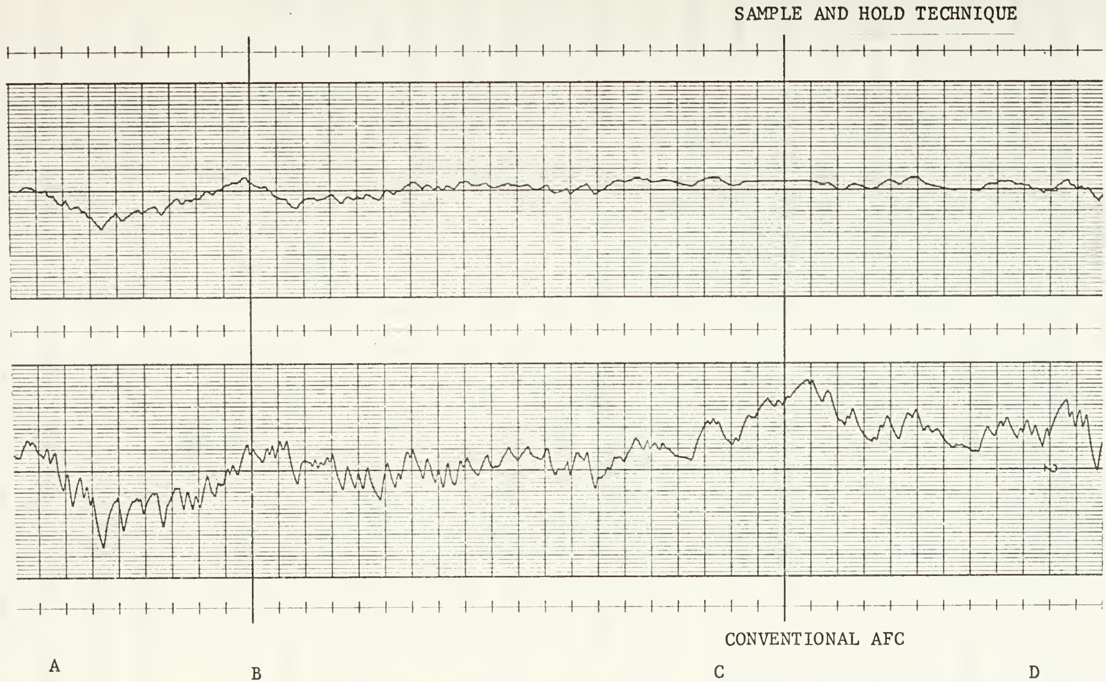


FIG. 19 RESPONSE WITH RANDOM FREQUENCY CHANGES

CONCLUSIONS

This thesis has presented an alternate method for obtaining an error correcting voltage for automatic frequency control in binary data transmission. This method has been explained in detail and the results obtained have been compared with those of a conventinal AFC method.

The experimental results of this investiagation demonstrate that the sample-and-hold technique can be used in any binary data transmission system, in order to improve the error rate caused by interferences due to noise and selective fading. In this report a standard teletype signal was used as a representative binary system.

For the different cases chosen for comparison, a satisfactory improvement with respect to the conventional AFC method was obtained. The sample-and-hold method is almost insensitive to short drifts in frequency due to fading, especially if the time of fading is short with respect to the holding period. The method appears promising because of the ease of realization, simplicity of the circuits and the estimated minimal cost.

Besides the use of this technique in automatic frequency control, it could be used for the measurement of the center frequency of an FSK or FM signal. If a voltage $E_o = \frac{E_m + E_s}{2}$ can be derived from the sample-and-hold circuit, a measure of the average signal frequency would be obtained:

$$f_{ave} = \frac{f_m + f_s}{2}$$

Since the sample are made of the peak values, intermediate values of the signal frequency, occurring between sample intervals and during the holding time, would have no effect on the value of E_o. The realization of such a system could be used as a frequency meter to measure the center

frequency of a RTTY signal, of an FM Signal, or, if the amplitude variations were removed by an amplitude limiting circuit, of a Single-Sideband signal. In the later case, E_0 combined with a proper off-set voltage, might be used for automatic tuning in the reception of Single-Sideband.

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ABSTRACT

A method of deriving a voltage for automatic frequency control of a radio-teletype receiver-converter is developed and tested. By sampling and holding the amplitude of the "Mark" and "Space" signals out of an FSK detector, comparing and integrating their difference, an error correcting voltage results which is less sensitive to noise and selective fading than the AFC voltage derived in the usual way. A sample-and-hold circuit is described. Comparative performance tests, with data in the form of strip-chart recordings, confirms the claims made for the technique.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Binary Data Transmission						
Automatic Frequency Control						
Frequency Shift Keying						
Selective Fading						